Application of Grids, Clouds & High-Performance Computing in Research of Urbanization

Earth, Environmental Science & Biodiversity II: Urbanization

1400 to 1530; March 18, 2015 (Wednesday)

Conference Room 2, BHSS, AS

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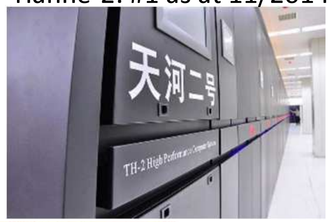
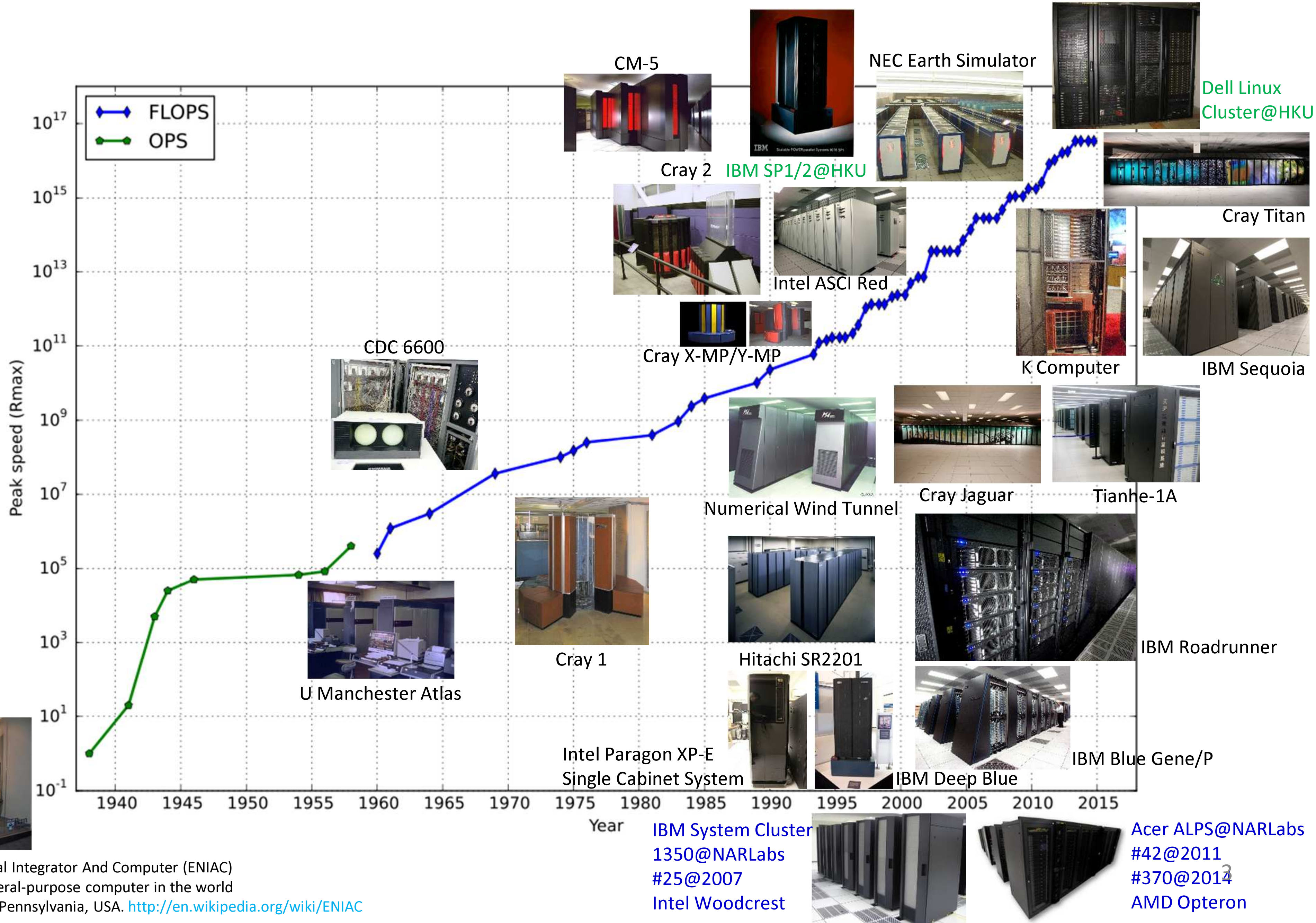
Outline

- High-Performance Computers (HPCs)
  - In the last ½ decades.
- Grids, clouds & HPC in our daily lives.
- Multi-scales in atmospheric motions.
- Research of urbanization (small to large scales).
  - Building information modeling (BIM).
  - Digital maps.
  - Geographic information system (GIS).
  - Air ventilation assessment (AVA).
  - Meso-scale meteorology modeling.
  - Global-scale climatology modeling.
  - Our research effort.
    - Engineering approach to atmospheric pollution problems.
- Conclusion.

High-Performance Computers

Tianhe-2: #1 as at 11/2014

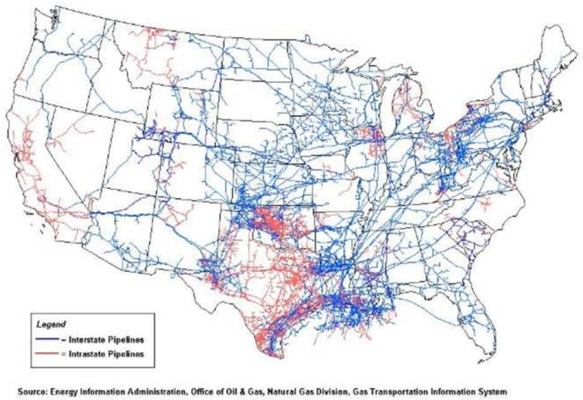




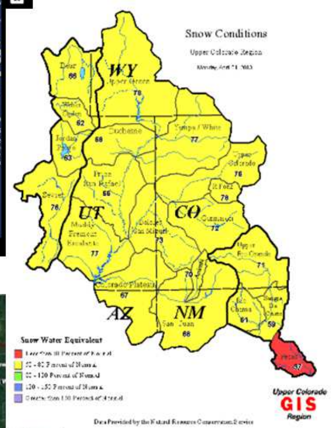
Electronic Numerical Integrator And Computer (ENIAC)
First electronic general-purpose computer in the world
1946, University of Pennsylvania, USA. http://en.wikipedia.org/wiki/ENIAC

Daily Lives

Google map



Pipeline & facility management



Weather, flooding & snowing

Stock market

Hospital admission

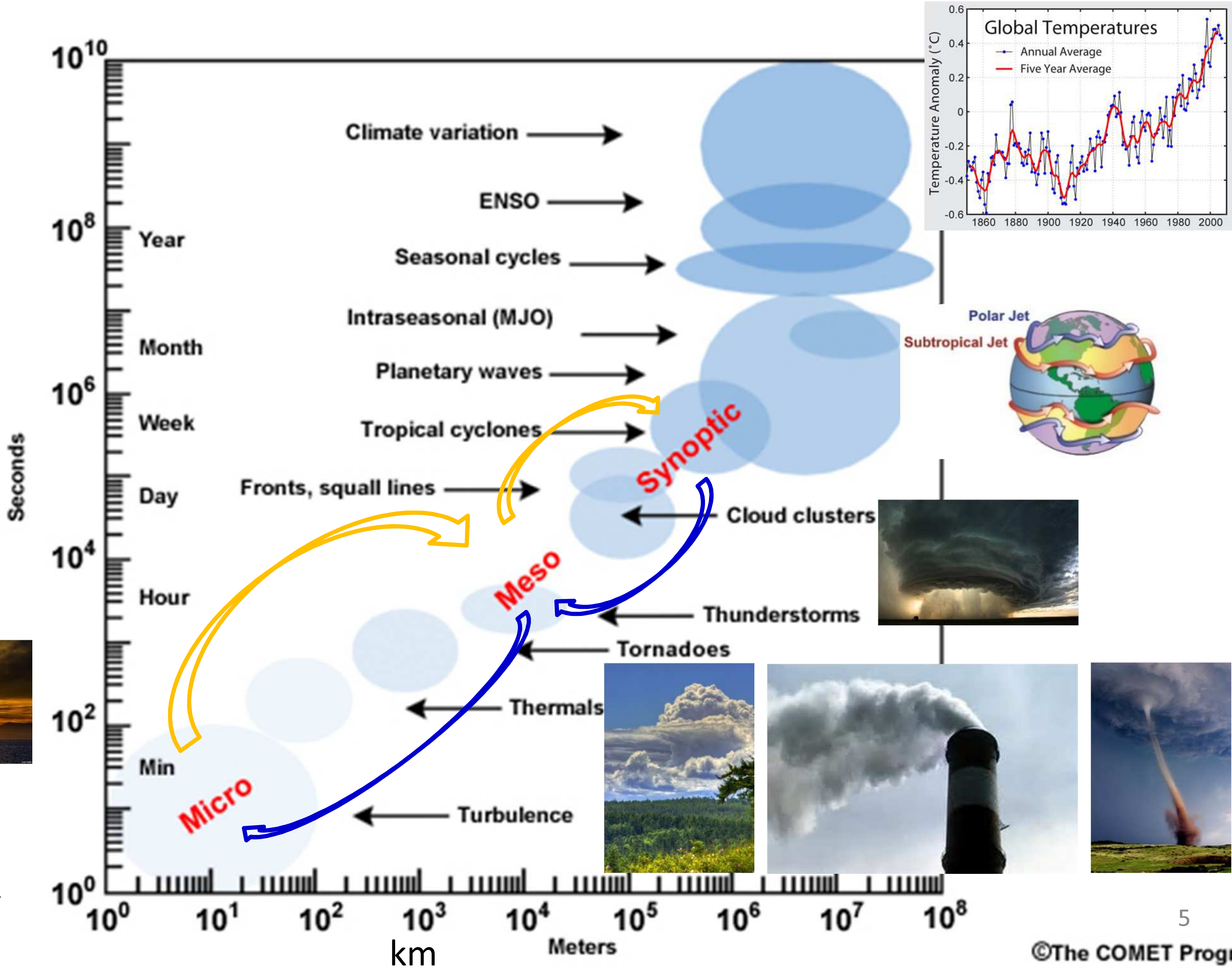
Entertainment

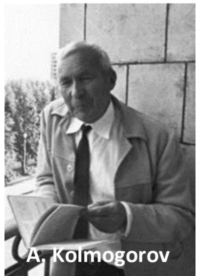
Traffic report

Cloud banking

Business cloud

Scales of Atmospheric Motions





TKE
dissipation
scale

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

http://www.goes-r.gov/users/comet/tropical/textbook_2nd_edition/print_3.htm

Building Information Modeling (BIM)

- Digital representation of physical & functional characteristics of a facility.
- A shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.
  - Management of building information.
  - Construction management.
  - Facility operation.
- The Hong Kong Institute of Building Information Modelling

Building Information Modeling (BIM)

- Challenge
  - Increased coordination of construction documents.
  - Embedding & linking of vital information, such as vendors for specific materials, location of details & quantities required for estimation & tendering.
  - Improved productivity due to easy retrieval of information.
  - Improved visualization.
  - Increased speed of delivery
  - Reduced cost.
- Extension to building energy performance & green building.
- Enable the searching & use of massive datasets in m secs.
- Standardized & virtualized commodity infrastructure.
- Enable real-time continuous processing of open digital document/information flows.

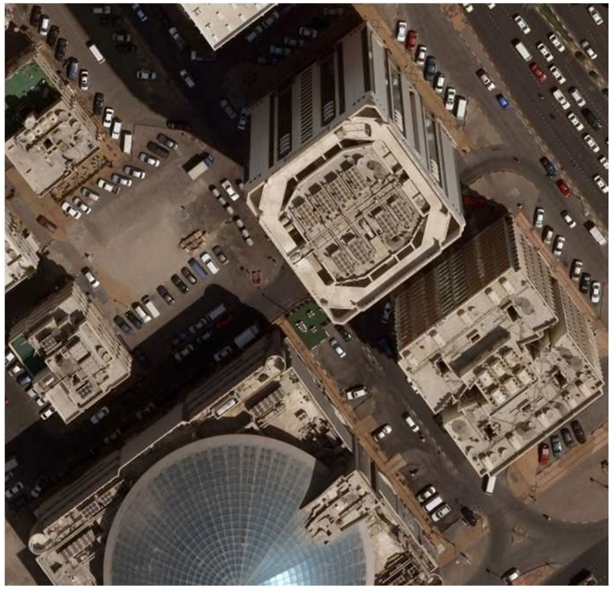
https://www.youtube.com/watch?v=hgyhRk8smkk

BIM models help the team visualize where to place the project's 3 tower cranes safely within the building's tight site.

http://southwest.construction.com/features/archive/2009/0709_F2_CityScape.asp

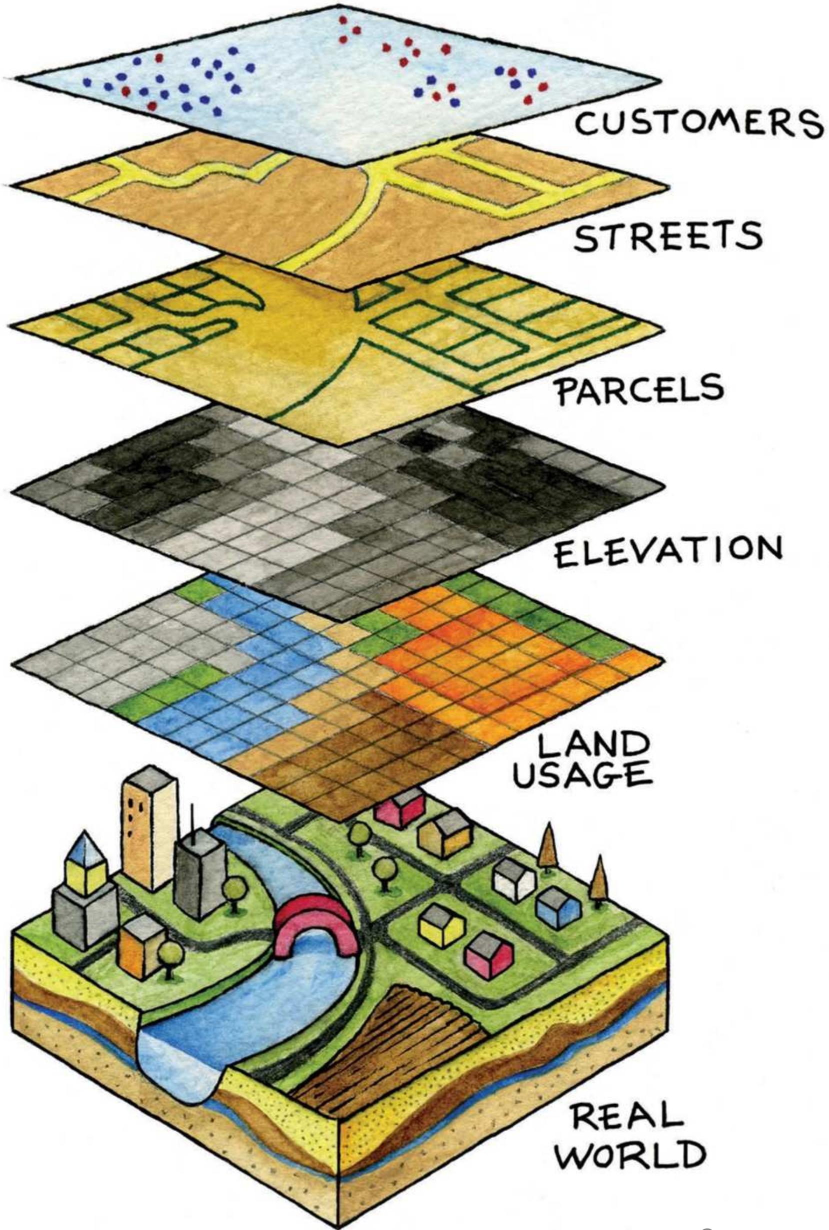
Digital Maps/Orthophoto

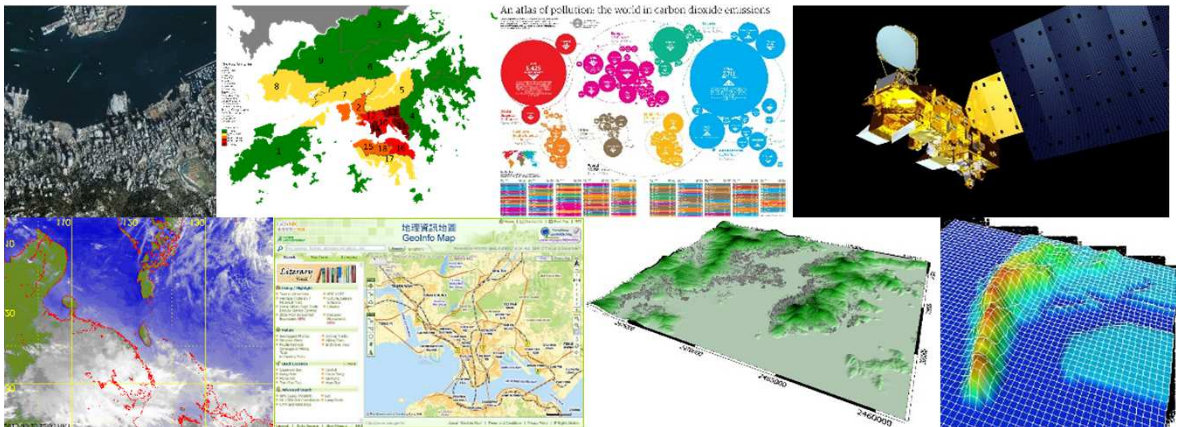
- Derived from aerial photographs.
- Ground pixel 0.5 m $\times$ 0.5 m.
- Useful to architects, engineers & planners in development projects.
- Dataset for GIS & AVA studies.



Geographic Information System (GIS)

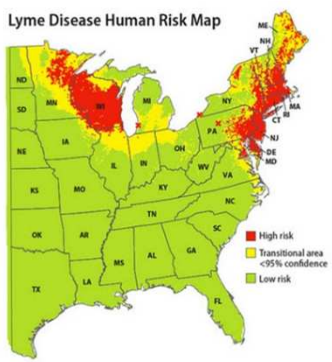
- A system designed to capture, store, manipulate, analyze, manage, & present all types of spatio-temporal or geographical data.
- Visualization of GIS data over the internet (or mobile devices).
- Uses spatio-temporal location as the key index for all other information.
- Survey data & remote sensing
  - Satellite images: MTSAT IR, EOS MODIS & NOAA/METOP, etc.
  - Underground utility services.
  - Atmospheric data?





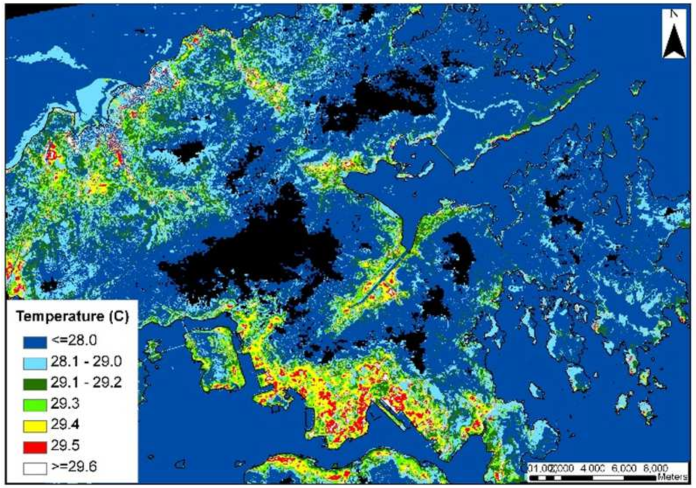
Geographic Information System (GIS)

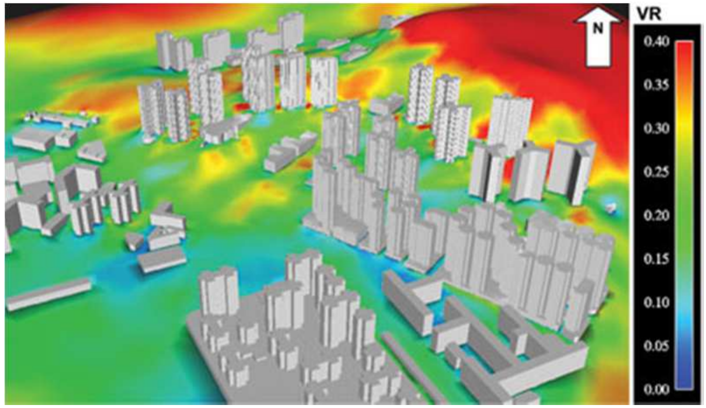
- Challenge
  - 3 product segments
    - Software, data & services.
  - Availability of low-cost GIS equipment.
    - Customized GIS applications/solutions in line with specific industry requirements.
  - Increased adoption of GIS application in mobile computing devices.
  - GIS, data mining & big data.
    - Findings from GIS datasets.
    - New algorithms for data infrastructure.
    - Collaboration among various parties
      - Machine learning & complex process modeling.
    - Quality & uncertainty in big data.
    - Analytic & visualization solutions.
  - Data network, stream-processing engines for real-time analysis, spatially-enabled databases & search engines.
  - Data consolidation from different parties.

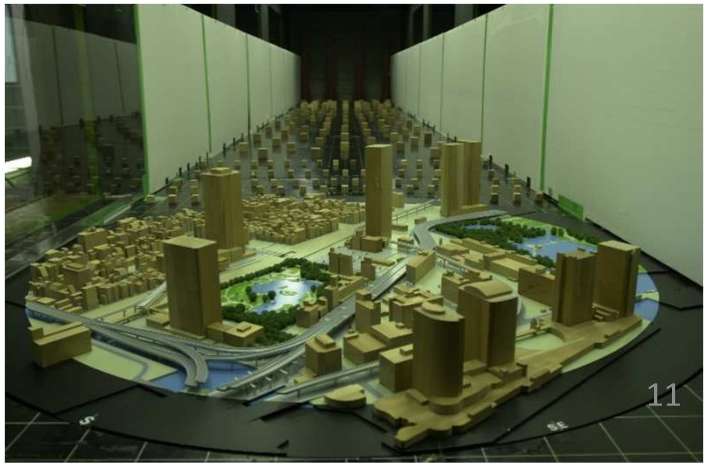


Air Ventilation Assessment (AVA)

- Initiative to identify measures to improve the living environment.
- Effective airflow in the external macro built-up environment which would not lead to adverse or restricted conditions to cause human discomfort or be unfavorable for the predominant land use activities.
- Buildings in the (new) development project are solved explicitly.
- An indicator to ground-level ventilation.
- Reduction/enhancement of ground-level wind speed (compared with free-stream flow).
- Laboratory measurements or computer modeling (CFD).
- Mean wind speed & turbulent quantities.

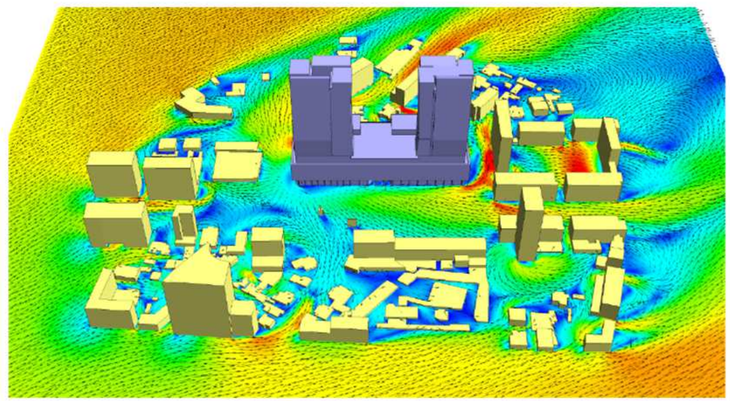






Air Ventilation Assessment (AVA)

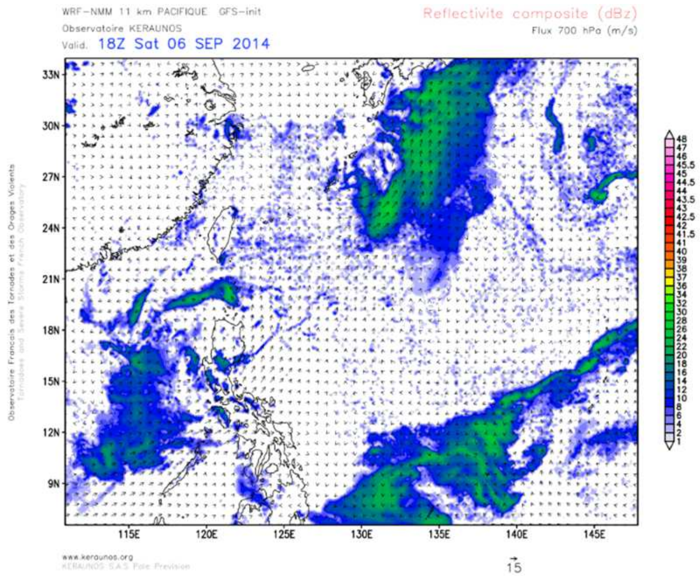
- Challenge
  - Formulation of guidelines & standards.
  - Modeling
    - Turbulence models (RANS or LES?).
    - Necessity of transient simulation.
    - Energy from buildings.
    - Other than isothermal conditions
  - Computing
    - Details of the buildings.
    - Size of computational domain.
    - Spatial resolution requirement.
    - Coupling between difference scales.
  - Grid/Cloud
    - Update of building, terrain & meteorological information from various sources.
    - Post-evaluation of modeling results.
    - Large-scale computation using grids or clouds.
    - Results availability & user-friendly interface.

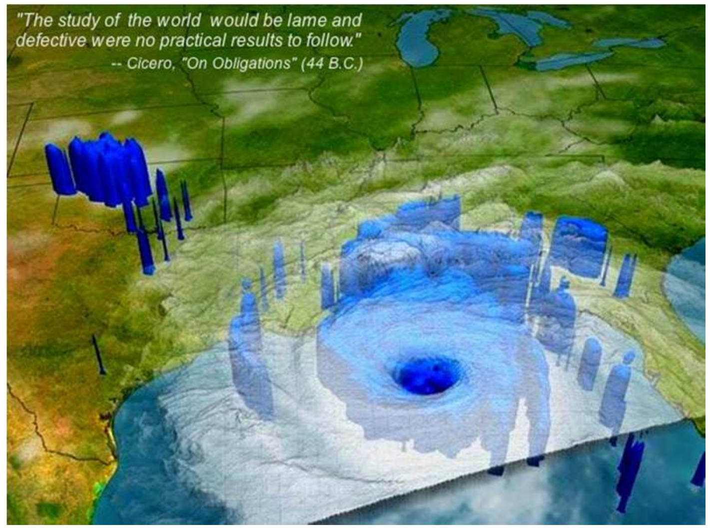


Air patterns around a building and its environment.

Meso-scale Meteorology Modeling

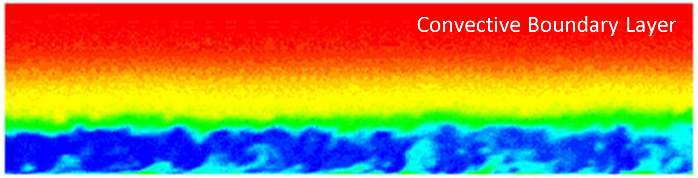
- Numerical weather prediction (NWP) models that have a horizontal grid spacing 1 km ≤ Δx ≤ 15 km.
  - Weather Research & (WRF) Forecasting model.
  - Regional Atmospheric Modeling (RAM) System.
  - Meso-scale Meteorological Model (MM5).
  - Area-oriented Numerical Simulation & Environmental Assessment Modeling System (ANEMOS).
  - Meso-scale Compressible Community Model (MC2)
  - Met Office Unified Model (UM).
- Weather forecast, hurricane, tropical cycle, tornado, thunderstorm, mountain/valley/sea breezes & wind energy assessment.
- Parameterizations
  - Land surfaces.
  - Vegetation & built environment
  - Subgrid-scale (SGS) processes.
  - Convection.
  - Energy & water balance.
- Grid nesting for initial & boundary conditions.
  - Coupling with global models.
  - Data assimilation system.





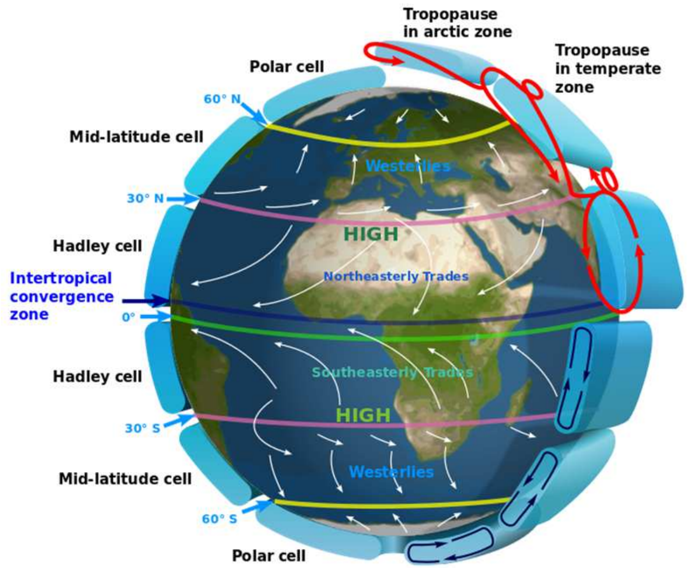
Meso-scale Meteorology Modeling

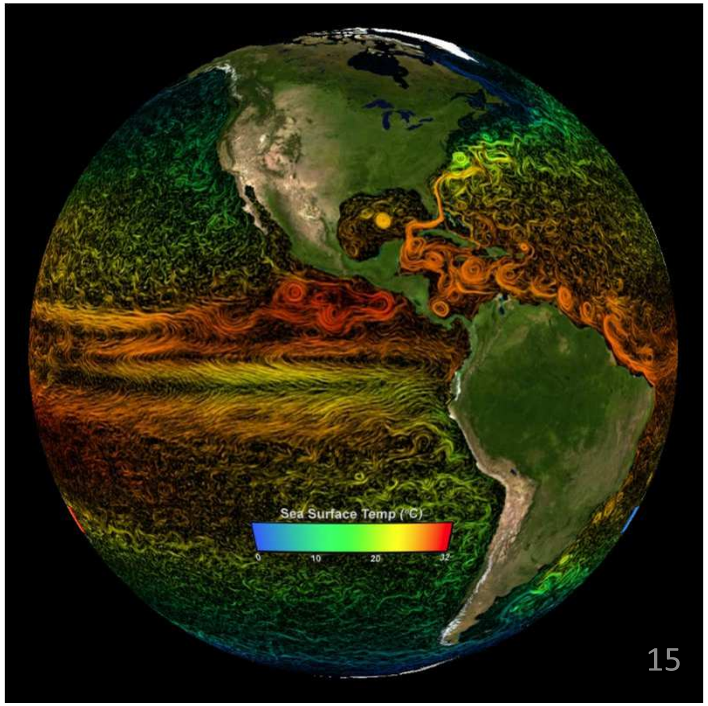
- Challenge
  - Parameterizations & microphysics.
  - Coupling with other systems such as cities or sea wave.
  - Solar radiation.
  - Computing
    - Spatial resolution (hardly solves < 5 Δx) & grid nesting.
    - Able to resolve topographic but unlike buildings.
    - Surface roughness?
  - Grids & Clouds
    - Initial & boundary conditions
      - Obtained from global models (e.g. ECMWF or NWS).
      - Global monitoring (data assimilation) via WMO.
    - Spin-up time.
    - Probabilistic forecasting & real-time simulation.
    - Community effort.



Global-scale Climatology Modeling

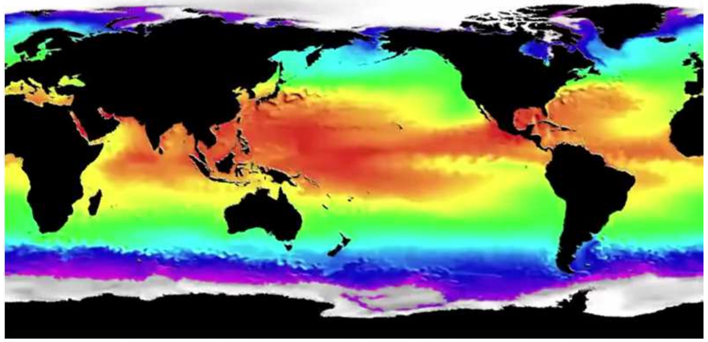
- Study of weather patterns related to the transport processes from the tropics to the poles & very large-scale oscillations (of time period months or years).
- A mathematical model based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation & latent heat).
  - Navy Operational Global Atmospheric Prediction System (NOGAPS).
  - Community Earth System Model (CESM).
  - GEOS-Chem.
  - Model for Interdisciplinary Research on Climate (MIROC).
  - Meteorological Research Institute Atmospheric General Circulation Model (MRI-GCM).
  - Hadley Centre General Circulation Model (GCM)
- Understand the climate & predict climatic changes.
- Coupled with
  - Atmospheric model.
  - Oceanic & sea-ice model.
  - Land-surface model.
  - Solar radiation.

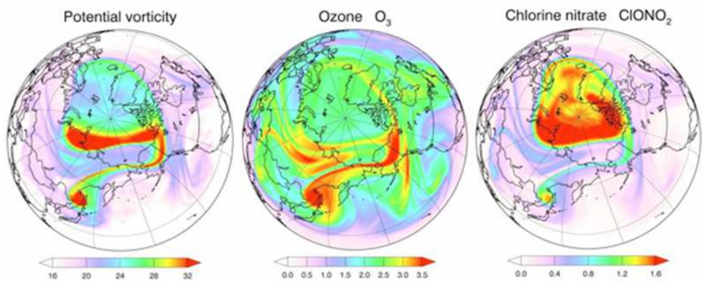


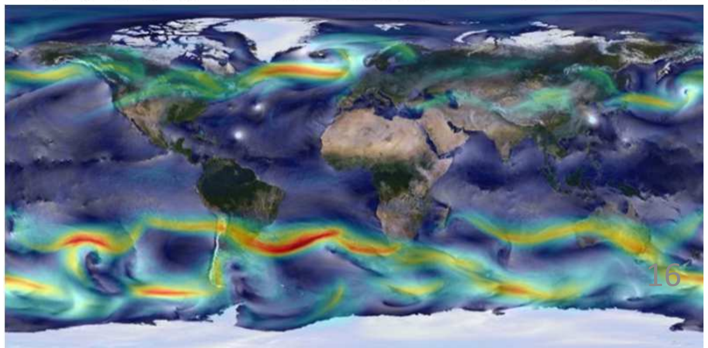


Global-scale Climatology Modeling

- Challenge
  - Atmospheric chemistry, constituents, ecosystems & climate.
  - Climate projections & forecasts.
  - Role of land surface in climatic change.
  - Ocean & climate.
  - Grids, clouds & computing
    - High-resolution atmospheric components.
    - Full coupling among various components.
    - Scalability & multi-core architecture.
    - Parallel I/O
  - Data sharing & assimilation.
  - Global observational data.



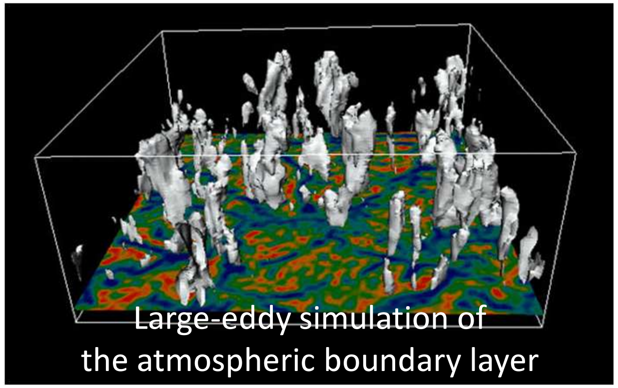




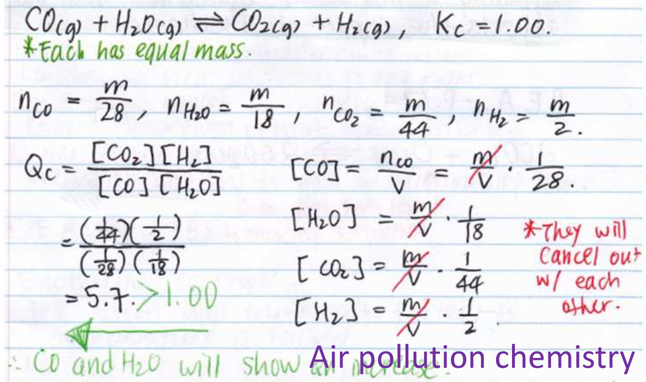
Research Interest

- Air Pollution Physics & Chemistry
- Geophysical Turbulence
- Scientific Computing

- Mathematical modeling of turbulence
  - Direct numerical simulation (DNS)
  - Large-eddy simulation (LES)
  - Reynolds-averaged Navier-Stokes (RANS) equations/turbulence
- Mathematical methods
  - Finite element method (FEM)
  - Finite volume method (FVM)
- Laboratory instrumentation
  - Wind tunnel
  - Water channel


Large-eddy simulation of the atmospheric boundary layer

10^3 to 10^4 m



Air pollution chemistry

10 to 10^3 sec

Meteorology

Pollution chemistry

Atmospheric turbulence & stratification on pollutant transport

large-scale

Nonlinear & tightly coupled chemistry among pollutants

Chemical species


Air pollution in the atmospheric boundary layer

Environmental fluid mechanics

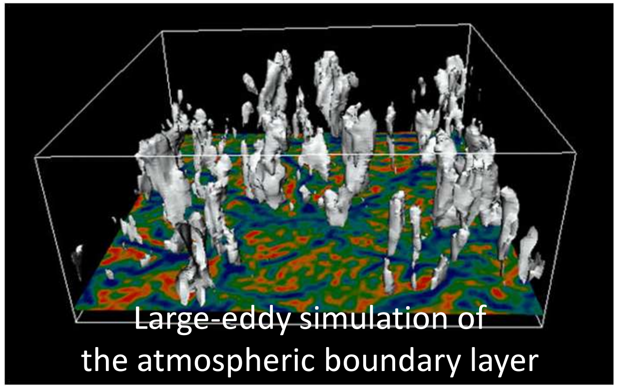
Wakes & local turbulence production around buildings

small-scale


Large-eddy simulation of the flows around buildings

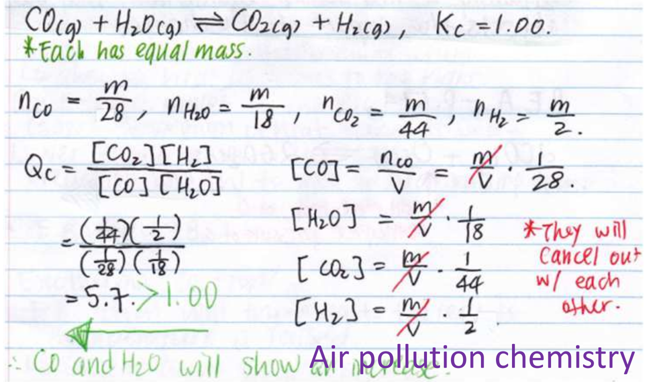
1 to 10^2 m

Current Approach



Large-eddy simulation of the atmospheric boundary layer

- Stratification & convective current on chemistry
- Weak pollutant dilution in stable stratification
- Pollutant concentrations on energy budget
- Phase change of H_2O



Air pollution chemistry

Meteorology

Pollution chemistry

- Surface roughness & drag force
- Anthropogenic & natural emission
- Wind shear & TKE production
- Momentum entrainment & subsidence
- Updraft/downdraft
- Natural terrain & building configuration
- Stratification & convective current

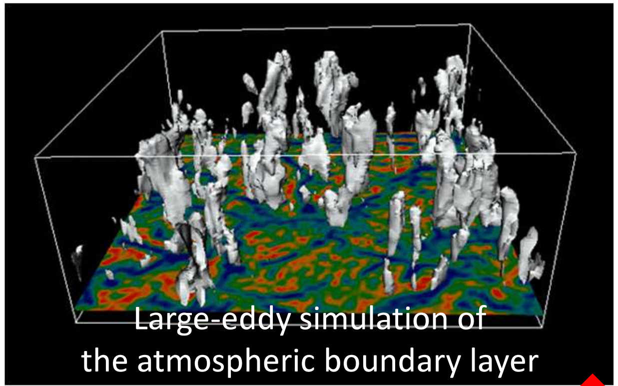
Air pollution in the atmospheric boundary layer

- Prolonged pollutant retention in the urban canopy layer
- Inhomogeneous pollutant distribution
- Enhanced pollutant dilution & mixing around buildings
- In the vicinity to ground-level pollutant sources
- Coupled pollutant mixing & chemistry
- Emission inventory

Environmental fluid mechanics

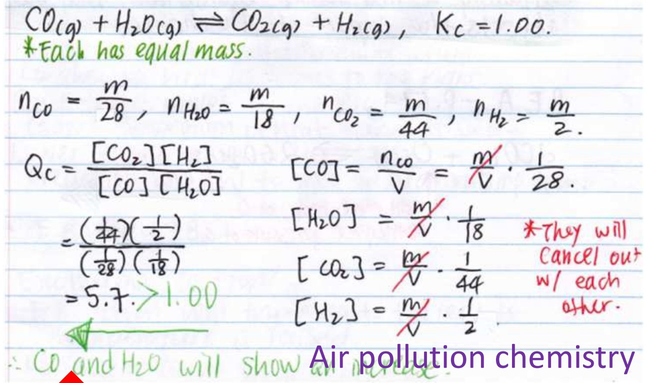
Large-eddy simulation of the flows around buildings

In fact they couple with each other


Large-eddy simulation of the atmospheric boundary layer

How to handle the broad range of scales

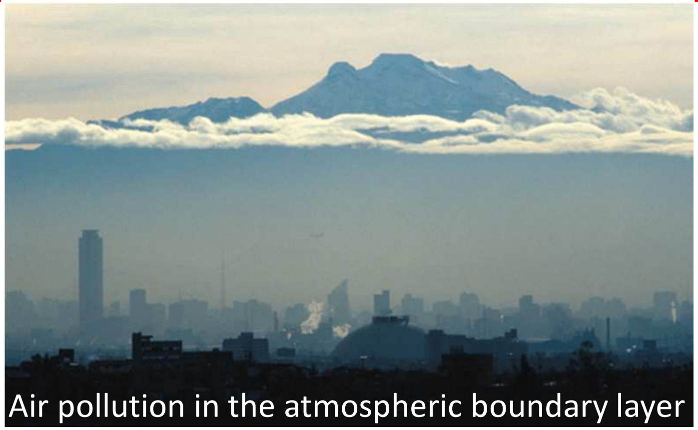
Challenge in computational engineering & scientific computing



Air pollution chemistry

Meteorology

Pollution chemistry


Air pollution in the atmospheric boundary layer

How the near-ground small scales interact with the large scales in the atmospheric boundary layer, & their collective effects on pollutant transport

Challenge in environmental fluid mechanics & atmospheric dynamics

How urban morphology affects pollution chemistry, composition, & retention in the urban atmospheric/canopy layer

Challenge in urban climate & atmospheric chemistry

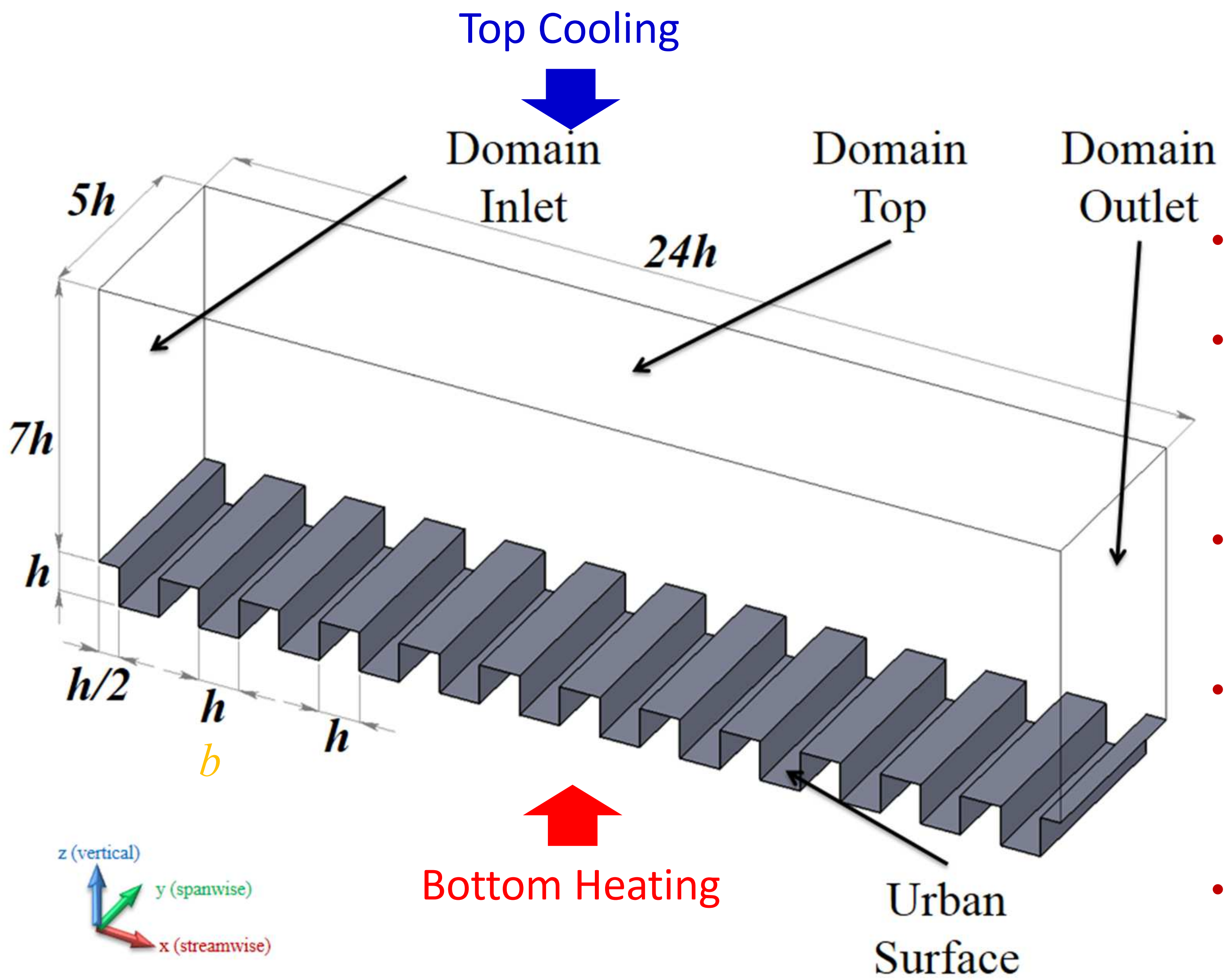
Environmental fluid mechanics


Large-eddy simulation of the flows around buildings

Integrated Approach

- Long-Term Impact & Significance
  - Improved understanding of air pollution physics & chemistry over urban areas.
  - Emission parameterizations for chemical species.
  - Recommendation for urban planning & environmental management.
- International Scientific Community
  - University of Reading, University of Birmingham, University of Southampton, Universität Hamburg, University of Oklahoma, Metro France, National Center for Atmospheric Research, & Central Research Institute of Electric Power Industry (Japan), etc.
- Our niche research area
  - Use Hong Kong as a platform to examine urban air pollution then apply the theory to elucidate the problems in other cities in the world.
  - On-going research projects in large-eddy simulation & air pollution chemistry over idealized urban areas.

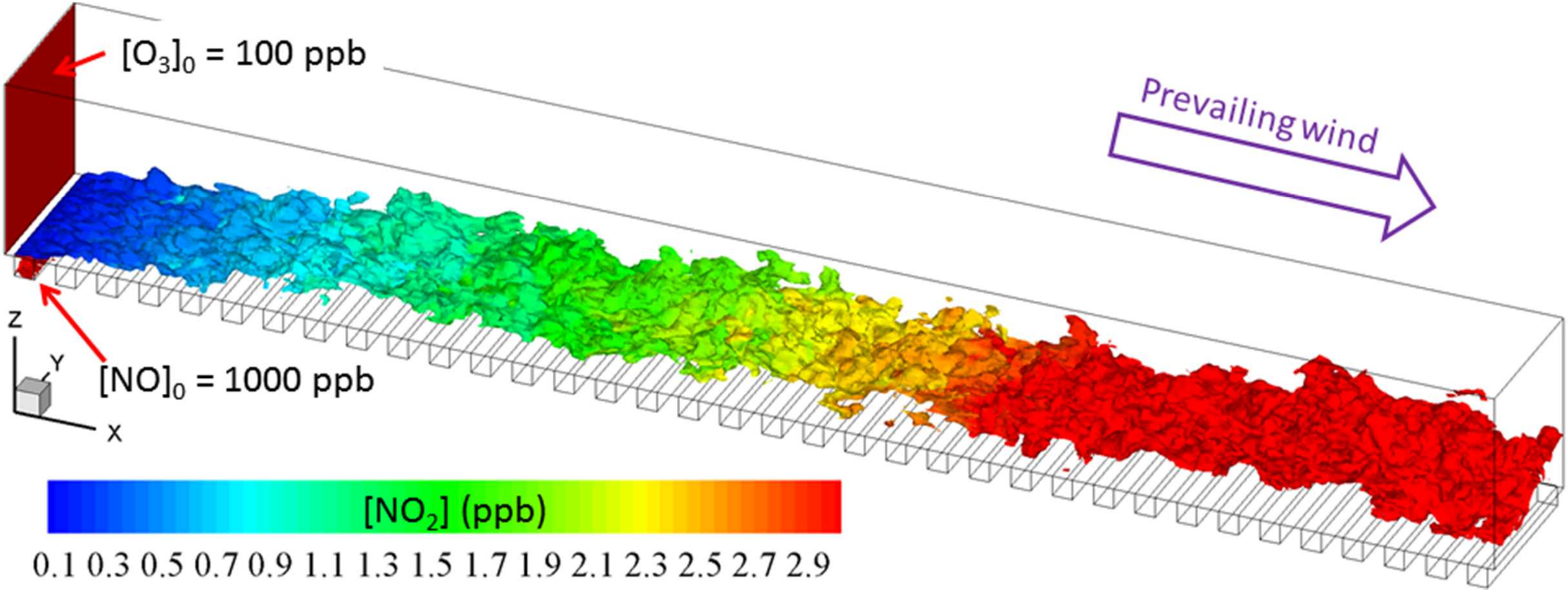
Methodology



- Hypothetical rough/urban surfaces
- Horizontally homogeneous domain & cyclic boundary conditions (BCs).
- (Background) pressure gradient ΔP_x in the streamwise direction.
- Large-eddy simulation (LES) with the one-equation subgrid-scale (SGS) model.
- Change the aspect ratio (AR = h/b) to control the aerodynamic roughness.

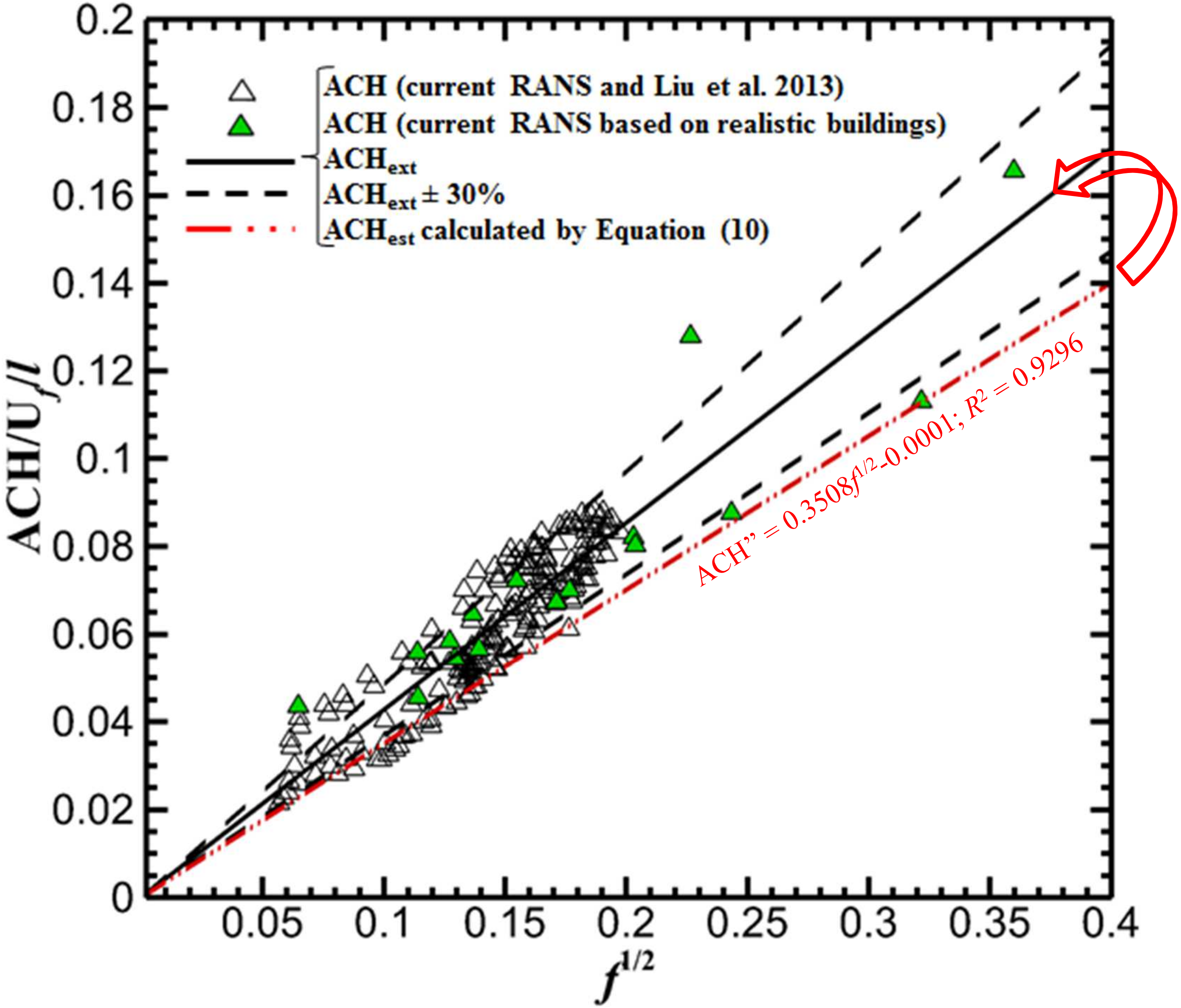
Methodology

Preliminary Results



- Snapshot of chemically reactive pollutant (NO_x-O_3) plume dispersion over idealized urban street canyons. Nitric oxide is released from the 1st street canyon into the urban canopy/atmospheric boundary layer.
- Nitrogen oxide concentration is high at the ground level, drops sharply at the roof level, then increases gradually in the streamwise direction.

Estimator



ACH (current RANS and Liu et al. 2013)
ACH (current RANS based on realistic buildings)
ACH_{ext}
$ACH_{ext} \pm 30\%$
ACH_{est} calculated by Equation (10)
ACH' = $0.3508f^{1/2}$-0.0001; R^2 = 0.9296
$ACH/U_f/l$
$f^{1/2}$
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Pollutant Dispersion Parameterization

- Advection-diffusion equation

$$U\frac{\partial c}{\partial x} = K\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) + Q\delta(x, y, z)$$

$$\boxed{c(x, y, z) = \frac{Q}{4\pi K r}\exp\left[-\frac{u(r - x)}{2K}\right]}$$

where $r^2 = x^2 + y^2 + z^2$

- Advection-diffusion equation with chemistry

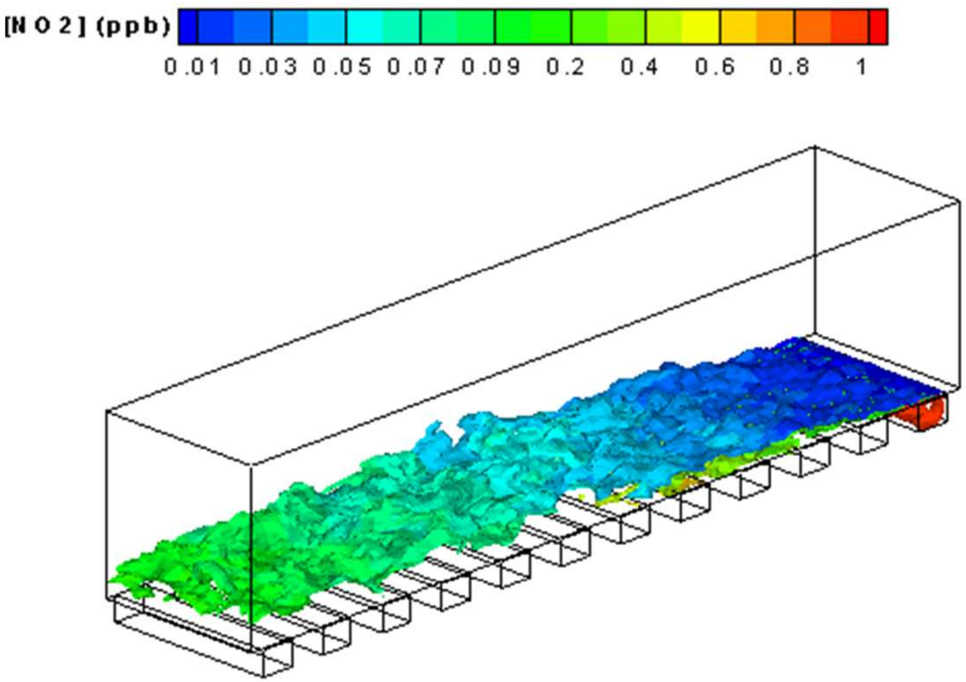
$$U\frac{\partial c}{\partial x} = K\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) - Lc + Q\delta(x, y, z)$$

$$\boxed{c(x, y, z) = \frac{Q}{4\pi K r}\exp\left[-\frac{(u^2 + 4KL)^{1/2} r - ux}{2K}\right]}$$

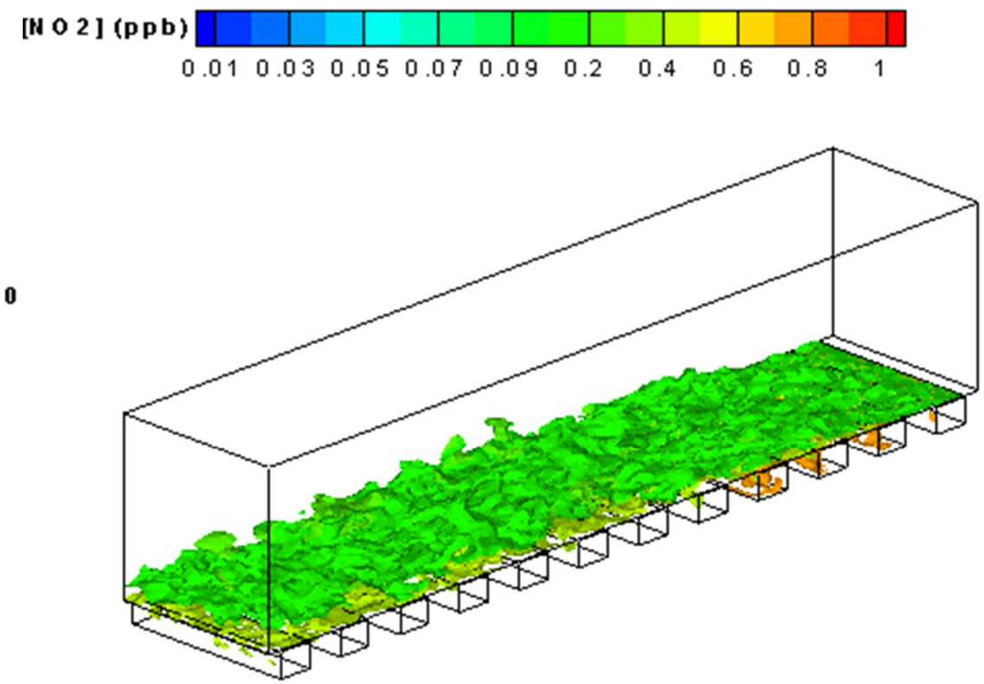
Parameterization of K over urban surfaces.

Collective effect of K & L on pollutant distribution & chemistry.

Preliminary Results



[N O] iso-surfaces: 10, 100 & 3000



[O 3] iso-surfaces: 0.2, 0.5 & 0.8 ppb

Conclusion

- A quick review on the use of grids, clouds & high-performance computing (HPC) in the research related to urbanization.
- Grids
  - Field observation monitoring, data assimilation & post-processing.
- Clouds
  - Analytic methods, big data sharing & community effort.
- High-performance computing
  - Modeling of atmospheric processes.
  - Multi-scale requirement, detailed multi-physics/chemistry & parallelism.

Acknowledgment

- Thanks for the invitation from **International Symposium on Grids & Clouds 2015**
- We gratefully acknowledge the **Hong Kong Research Grants Council (RGC)** for financial supports.
- Part of the research project is conducted using the HKU Information Technology Services (ITS) research computing facilities that are supported in part by the **Hong Kong UGC Special Equipment Grant (SEG HKU09)**.